

STUDY OF TWO-PHOTON PRODUCTION PROCESS IN PROTON-PROTON COLLISIONS BELOW THE PION PRODUCTION THRESHOLD

A.S.Khrykin

Joint Institute for Nuclear Research, Dubna, 141980 Russia

Email: Khrykin@nusun.jinr.dubna.su

Abstract

The energy spectrum for high energy γ -rays ($E_\gamma \geq 10$ MeV) from the process $pp \rightarrow \gamma\gamma X$ emitted at 90° in the laboratory frame has been measured at an energy below the pion production threshold, namely, at 216 MeV. The resulting photon energy spectrum extracted from $\gamma - \gamma$ coincidence events consists of a narrow peak at a photon energy of about 24 MeV and a relatively broad peak in the energy range of (50 - 70) MeV. The statistical significance for both the narrow and broad peaks exceeds 5σ . This behavior of the photon energy spectrum is interpreted as a signature of the exotic dibaryon resonance d_1^* which is assumed to be formed in the radiative process $pp \rightarrow \gamma d_1^*$ followed by its electromagnetic decay via the $d_1^* \rightarrow pp\gamma$ mode. The experimental spectrum is compared with those obtained by means of Monte Carlo simulations.

Key-words: Nucleon-Nucleon interactions, bremsstrahlung, two-photon production, multi-quark states.

1 Introduction

Direct-production of two hard photons in nucleon-nucleon collisions ($NN\gamma\gamma$) at intermediate energies, unlike production of single photons (NN bremsstrahlung), belongs to those fundamental processes which are still poorly explored both theoretically and experimentally. However, a study of this process can provide us with new important information on the underlying mechanisms of the NN interaction that is complementary to that obtained from investigations of other processes. In particular, the $NN\gamma\gamma$ process can be used as a sensitive probe for experimental verification of the possible existence of NN -decoupled nonstrange dibaryon resonances. These are two-baryon states 2B with zero strangeness and exotic quantum numbers, for which the strong decay ${}^2B \rightarrow NN$ is either strictly forbidden by the Pauli principle (for the states with the isospin $I = 1(0)$ and with an even sum $L + S + I$, where L is the orbital momentum and S is the spin), or is strongly suppressed by the isospin selection rules (for the states with $I = 2$) [1, 2]. Such dibaryon states cannot be simple bound systems of two color-singlet nucleons, and a proof of their existence would have consequences of fundamental significance for the theory of strong interactions. The NN -decoupled dibaryon states are predicted in a series of QCD -inspired models [3, 4, 5]. Among the predicted dibaryons, there are those with masses both below and above the pion production (πNN) threshold. The NN -decoupled dibaryons with masses below the πNN threshold are of special interest, since they may decay mainly into the $NN\gamma$ state, and consequently, their widths should be very narrow ($\leq 1\text{keV}$). Narrow dibaryon states have been searched for in a number of experiments [6], but none has provided any undoubted

evidence for their existence. Most of the past searches, however, were limited to dibaryons coupled to the NN channel, and, to our knowledge, only a few ones were dedicated to the NN -decoupled dibaryons[7, 8]. At the same time, since the latter do not couple to the NN -channel, then, depending on their production and decay modes, they may have escaped detection up to now and may naturally appear in dedicated experiments.

If the NN -decoupled dibaryons exist in nature, then the $NN\gamma\gamma$ process may proceed, at least partly, through the mechanism that directly involves the radiative excitation $NN \rightarrow \gamma \ ^2B$ and decay $\ ^2B \rightarrow \gamma NN$ modes of these states. In NN collisions at energies below the πNN threshold, these production and decay modes of the NN -decoupled dibaryon resonances with masses $M_R \leq 2m_N + m_\pi$ would be unique or dominant. The simplest and clear way of revealing them is to measure the photon energy spectrum of the reaction $NN\gamma\gamma$. The presence of an NN -decoupled dibaryon resonance would reveal itself in this energy spectrum as a narrow line associated with the formation of this resonance and a relatively broad peak originating from its three-particle decay. In the center-of-mass system, the position of the narrow line(E_R) is determined by the energy of colliding nucleons ($W = \sqrt{s}$) and the mass of this dibaryon resonance as $E_R = (W^2 - M_R^2)/2W$. An essential feature of the two-photon production in NN collisions at an energy below the πNN threshold is that, apart from the resonant mechanism in question, there should only be one more source of photon pairs. This is the double NN -bremsstrahlung reaction. But this reaction is expected to play a minor role. Indeed, it involves two electromagnetic vertices, so that one may expect that the $NN\gamma\gamma$ -to- $NN\gamma$ cross section ratio should be of the order the fine structure constant α . However, the cross section for $NN\gamma$ is already small (for example, the total pp -bremsstrahlung cross section at energies of interest is a few μb). The process $pp \rightarrow pp\gamma\gamma$ at an energy below the πNN threshold provides an unique possibility of searching for the NN -decoupled dibaryon resonances in the mass region $M_R \leq 2m_p + m_\pi$ with quantum numbers $I(J^P) = 1(1^+, 3^+, \text{etc.})$ or those with $I = 2$ (J is the total spin, and P is the parity of a dibaryon). The preliminary experimental studies of the reaction $pp \rightarrow \gamma\gamma X$ at an incident proton energy of about 200 MeV[9, 10] showed that the photon energy spectrum of this reaction had a peculiar structure ranging from about 20 MeV to about 60 MeV. This structure was interpreted as an indication of the possible existence of an NN -decoupled dibaryon resonance(later called d_1^*) that is produced in the process $pp \rightarrow \gamma d_1^*$ and subsequently decays via the $d_1^* \rightarrow pp\gamma$ channel. Unfortunately, a relatively coarse energy resolution and low statistics did not allow us to distinguish the narrow γ -peak associated with the d_1^* production from the broad γ -peak due to the decay of this resonance and, hence, to determine the resonance mass exactly. To get a rough estimate of the d_1^* mass, we admitted that the expected narrow γ -peak is positioned at the center of the observed structure and thus obtained $M_R \sim 1920$ MeV. However, if the uncertainty in the position of the narrow γ -peak in the structure is taken into account, the actual d_1^* mass might be considerably different from such a crude estimate. The possible existence of this dibaryon resonance was also probed in the proton-proton bremsstrahlung data taken by the WASA/Promice Collaboration at the CELSIUS accelerator[11] for proton energies of 200 and 310 MeV. However, the trigger used in those experimental studies to select events was designed and optimized for investigating the usual $pp \rightarrow pp\gamma$ bremsstrahlung. The selected events were those corresponding to two simultaneously detected protons emerging in the forward direction at angles between 4° and 20° with respect to the beam axis, each of which had a kinetic energy exceeding the present threshold (40 MeV). The analysis of those data resulted only in upper limits on the dibaryon production cross section in the mass range

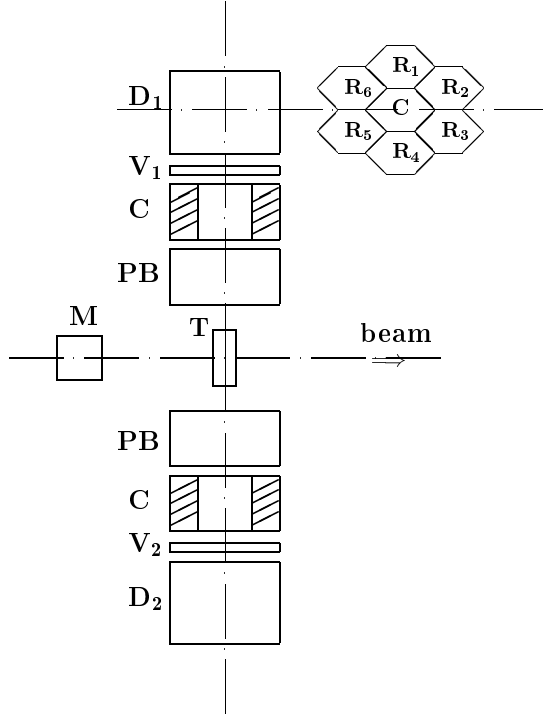


Figure 1: Schematic layout of the experimental setup

from 1900 to 1960 MeV. Therefore, to clarify the situation with the dibaryon resonance d_1^* , we have decided to measure the energy spectrum of the $pp \rightarrow pp\gamma\gamma$ reaction more carefully.

2 Experimental apparatus and event selection

The experiment was performed using the variable energy proton beam from the phasotron at the Joint Institute for Nuclear Research (JINR). The schematic layout of the experimental setup is shown in Fig. 1. The pulsed proton beam (bursts of about 7 ns FWHM separated by 70 ns) with an energy of about 216 MeV and an energy spread of about 1.5% bombarded a liquid hydrogen target (T). The average beam intensity was on the order of $3.6 \cdot 10^8$ protons/s and was monitored by an ionization chamber (M). The liquid hydrogen target was a cylindrical cryogenic vessel with a length of about 5 cm ($\sim 0.35 \text{ g/cm}^2$) and a diameter of 4.5, cm which had thin entrance and exit windows made from 100 μm thick mylar foil. Both γ -quanta of the reaction $pp\gamma\gamma$ were detected by two γ -ray detectors (D_1 and D_2) placed in a horizontal plane, symmetrically on either side of the beam at a laboratory angle of 90° with respect to the beam direction. The γ -detector D_1 was an array of seven individual detector modules (see Fig. 1): the central detector module (C) and six detector modules (R_1, R_2, \dots, R_6) surrounding the central detector module. Each detector module was a 15 cm thick CsI(Tl) crystal having a hexagonal cross section with an outer diameter of 10 cm. The detector modules R_1, R_2, \dots, R_6 (ring) were designed to measure the energy of secondary particles and photons leaving the central detector module C. Thus, the energy of each photon detected by the detector D_1 was determined by summing up the

energy deposited in the central detector module and the energies deposited in the detector modules of the ring. Besides, the ring was used as an active shielding from cosmic ray muons. The energy resolution of a single $CsI(Tl)$ crystal was measured to be about 13% for $E_\gamma = 15.1$ MeV. The second γ -ray detector D_2 was a cylindrical $NaI(Tl)$ crystal 15 cm in diameter and 10 cm in length. Compared to the detector D_1 , it had a poorer energy resolution for γ -rays with energies $E_\gamma > 10$ MeV. The detector D_2 was mainly designed to select $\gamma - \gamma$ coincidence events. To reject events induced by charged particles, plastic scintillators (V_1 and V_2) were put in front of each γ -detector. Both γ -ray detectors were placed in lead houses with walls 10 cm thick which were in turn surrounded by a 5 cm borated parafin shield. The solid angles covered by the detectors D_1 and D_2 were 43 msr and 76 msr, respectively. To attenuate prompt particles coming from the target, 15 cm polyethylene bars (PB) were placed in between the target and each γ -detector.

The electronics associated with the γ -detectors and the plastic scintillators provided amplitude and time signals suitable for digitizing by an *ADC* and a *TDC*. The data acquisition system was triggered by the time signal from the detector module C which started all the *TDCs* and opened the *ADC* gates. In parallel, the time signals from the detector module C and the γ -detector D_2 were sent to a coincidence circuit to select those events which had signals from both the γ -detectors. Events satisfying this criterion were recorded in the event-by-event mode on the hard disk of the computer. A further selection of $\gamma - \gamma$ coincidence candidate events was done during off-line data processing.

The off-line selection procedure for events associated with the process $pp \rightarrow \gamma\gamma X$ included the following main operations: rejection of events induced by charge particles coming from the target, rejection of events induced by cosmic ray muons, selection of events which are caused by proton beam bursts and selection of events associated with $\gamma - \gamma$ coincidences.

3 Results and discussion

The measurements were performed both with the target filled with liquid hydrogen and with the empty one. Data for the full and empty targets were taken in two successive runs for ~ 31 h and ~ 21 h, respectively. The integrated luminosity of about 8.5 pb^{-1} was accumulated for the measurement with the full target. The resulting number of $\gamma - \gamma$ coincidence events associated with the $pp \rightarrow \gamma\gamma X$ process as a function of the photon energy measured by the detector D_1 is presented in Fig. 2. As can be seen, the energy spectrum of the reaction $pp \rightarrow \gamma\gamma X$ consists of a narrow peak at a photon energy of about 24 MeV and a relatively broad peak in the energy range from about 50 to about 70 MeV. It was found that the statistical significance for the sharp peak as well as for the broad one exceeds 5σ . The width (FWHM) of the narrow peak was found to be about 8 MeV. This width is comparable with that of the energy resolution of the experimental setup. The observed behavior of the photon energy spectrum agrees with a characteristic signature of the sought dibaryon resonance d_1^* that is formed and decays in the radiative process $pp \rightarrow \gamma d_1^* \rightarrow pp\gamma\gamma$. In that case the narrow peak should be attributed to the formation of this dibaryon, while the broad peak should be assigned to its three-particle decay. Using the value for the energy of the narrow peak $E_R \sim 24$ MeV, we obtained the d_1^* mass $M_R \sim 1956$ MeV.

Having assumed that the $pp \rightarrow \gamma d_1^* \rightarrow pp\gamma\gamma$ process with the d_1^* mass of 1956 MeV is the only mechanism of the reaction $pp \rightarrow pp\gamma\gamma$, we calculated the photon energy spectra of this reaction for a proton energy of 216 MeV. It was also assumed that the radiative decay

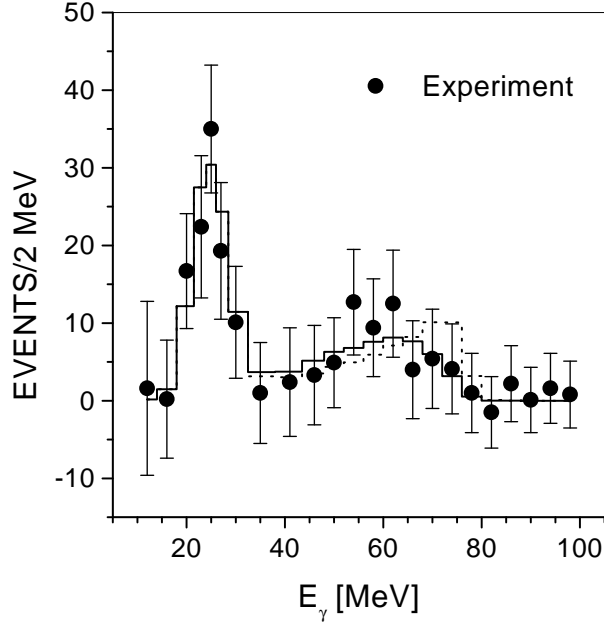


Figure 2: Experimentally observed energy spectrum for photons from the $pp\gamma\gamma$ process and energy spectra for photons from the process $pp \rightarrow \gamma d_1^* \rightarrow \gamma\gamma pp$ calculated with the help of Monte Carlo simulations for two d_1^* decay scenarios: without the FSI (solid line) and with the FSI (dashed line).

of the d_1^* is a dipole $E1(M1)$ transition from the two-baryon resonance state to a pp -state in the continuum. The calculations were carried out with the help of Monte Carlo simulations which included the geometry and the energy resolution of the actual experimental setup. The photon energy spectra were calculated for two different scenarios of the d_1^* decay. The difference between them was that one of these scenarios took into account the final state interaction (*FSI*) of two outgoing protons whereas in the other that interaction was switched off. Each of the scenarios imposed some restrictions on possible quantum numbers of the dibaryon state in question. The scenario including the *FSI* implies that the final pp -system is in the singlet 1S_0 state and consequently it should take place, in particular, for the isovector 1^+ dibaryon state (the simplest exotic quantum numbers), namely, $1^+ \xrightarrow{M1} 0^+$. At the same time, the scenario in which the *FSI* is switched off, is most likely to occur for the isotensor 0^+ dibaryon state. The spectra calculated for these two decay scenarios and normalized to the total number of $\gamma - \gamma$ events observed in the present experiment are shown in Fig. 2.

Comparison of these spectra with the experimental spectrum indicates that both the calculated spectra are in reasonable agreement with the experimental one within experimental uncertainties. However, one can see that the energy spectrum for the scenario that can be realized for the isotensor dibaryon ($I = 2$) is more consistent with the experimental spectrum. At the same time, the statistics of the experiment is insufficient to draw any firm conclusions in favor of one of these scenarios, that is, in favor of either $I = 1$ or $I = 2$ for the isospin of d_1^* . In this connection, we would like to emphasize that the experimental data on the process $\pi^- d \rightarrow \gamma\gamma X$ can shed some light on the properties of the dibaryon state we have observed. The point is that the d_1^* dibaryon can in principle be excited in this process via the mode $\pi^- d \rightarrow \gamma d_1^* \rightarrow \gamma\gamma nn$. However, excitation of the dibaryon d_1^* with isospin $I = 1$ is

allowed by the isospin selection rules, whereas excitation of the isotensor ($I = 2$) resonance is expected to be strongly suppressed[13]. Therefore, the preliminary results of the study of the reaction $\pi^- d \rightarrow \gamma\gamma X$ carried out by the RMC Collaboration at TRIUMF[12] indicating no enhancement of the two-photon yield in the process $(\pi^- d)_{atom} \rightarrow \gamma\gamma nn$ compared to the usual one-nucleon mechanism $\pi^- p \rightarrow \gamma\gamma n$ on the proton bound in the deuteron may imply that the d_1^* dibaryon has isospin 2.

4 Conclusion

The γ -ray energy spectrum for the $pp \rightarrow \gamma\gamma X$ reaction at a proton energy below the pion production threshold has been measured for the first time. The spectrum measured at an energy of about 216 MeV for coincident photons emitted at an angle of 90° in the laboratory frame clearly evidences the existence of the NN -decoupled dibaryon resonance d_1^* with a mass of about 1956 MeV that is formed and decays in the process $pp \rightarrow \gamma d_1^* \rightarrow pp\gamma\gamma$. The data we have obtained, however, are still incomplete, and additional careful studies of the reaction $pp \rightarrow pp\gamma\gamma$ are needed to get proper parameters (mass, width, spin, etc.) of the observed dibaryon state.

References

- [1] S.B.Gerasimov and A.S.Khrykin,Mod.Phys.Lett.**A8**,2457(1993).
- [2] S.B.Gerasimov,S.N.Ershov,A.S.Khrykin,Phys.At.Nucl.**58**,844(1995).
- [3] P.J.G.Mülders, A.T.M. Aerts, and J.J. de Swart, Phys.Rev. **D 21**,2653(1980).
- [4] L.A.Kondratyuk, B.V.Martem'yanov, and M.G.Schepkin,Sov.J.Nucl.Phys.**45**,776(1987).
- [5] V.B.Kopeliovich,Phys.At.Nucl.**58**,1317(1995).
- [6] B.Tatischeff et al.,Phys.Rev.C**59**,1878(1999).
- [7] W.Brodowski et al.,Z.Phys.**A355**,5(1996); R.Bilger,Nucl.Phys.**A629**,141c(1998).
- [8] L.V.Fil'kov et al.,Phys.Rev.C **61**,044004(2000).
- [9] A.S.Khrykin,in *Proceeding of the XIV International conference on particles and nuclei(PANIC96), Williamisburg, Virginia,USA,1996*, ed. by Carl E.Carlson and John J.Domingo,p.533.
- [10] A. S. Khrykin, πN Newsletter **13**,250(1997).
- [11] H.Calén et al.,Phys.Lett.**B427**,248(1998).
- [12] P.A. Zolnierczuk (The RMC Collaboration), Acta Phys.Polon.**B31**,2349(2000).
- [13] S.B.Gerasimov,in: *Proc. of the 13-th Int. Seminar on High Energy Physics Problems "Relativistic Nuclear Physics and Quantum Chromodynamics"*, edited by A.M. Baldin and V.V. Burov,Dubna,1998,v.II,p.3; nucl-th/9712064,nucl-th/9812077, nucl-th/9808070.